

# Columnar recombination: a tool for nuclear recoil directional sensitivity in a xenon-based direct detection WIMP search

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**Abstract.** A robust signal for sidereal anisotropy in nuclear recoils would support, perhaps more decisively than any other evidence, a discovery claim for a WIMP component of Dark Matter. I present a concept based on *columnar recombination in dense xenon gas*, sensing nuclear recoil direction relative to a TPC drift field. The central advance is that nuclear recoil directionality information is obtained through a comparison, event-by-event, of the ionization signal and recombination signal that are produced *prior* to drifting the track ionization. The optimum xenon density for this concept may be near ten bars, unlike conventional techniques that employ track visualization – with severe restrictions on gas density to about 1/10 bar. No restriction is imposed by diffusion during drift, facilitating the realization of a large monolithic room temperature xenon gas Time Projection Chamber at the ton-scale, with unprecedented sensitivity for both directionality and cross-section. Remarkably, the desired operating conditions for 0- $\nu\beta\beta$   $^{136}\text{Xe}$  experiment may be identical.

## 1. Introduction

An attractive candidate for Dark Matter (DM) is the Weakly Interacting Massive Particle (WIMP). As a remnant of Big Bang era, WIMPs should have interaction strength characteristic of weak interactions, although WIMP mass and interaction strength are not strongly constrained by theory. WIMP masses might lie in a wide range from well above normal heavy nuclei down to perhaps 10 GeV/c<sup>2</sup>. WIMP DM gravitationally captured in our galaxy is regarded as unlikely to co-rotate with the galactic plane. Independent of mass, WIMPs would have a truncated virial mean velocity of approximately 230 km/s. Earth's position in the galactic arm co-adds a velocity of ~220 km/s to a WIMP-nucleus collision in a terrestrial detector. A substantial anisotropy would thereby be induced in the distribution of nuclear recoil directions – most pronounced for the most energetic collisions. Local variations in the WIMP flow may be quite different from the simplest scenario, including even a negligible flux at earth, but we can only hope that Nature has not been that unkind to us. A recent review of the prospects for detecting directionality in WIMP flows can be found in [1].

The angle that the earth's rotation axis makes with the velocity of the galactic plane allows for automatic scanning with regard to putative WIMP flow direction from Cygnus. In figure 1, adapted from [1], the basic concept is illustrated.



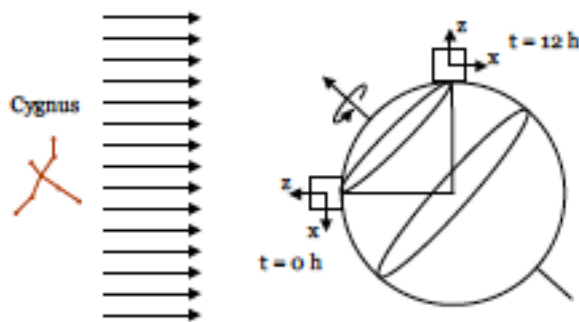


Figure 1. Under the assumption of a WIMP wind favoring the direction from Cygnus, a detector on earth observes sidereal anisotropy. At any latitude, the detector can be oriented to provide equal sensitivity. (figure is adapted from [1])

The discovery of sidereal anisotropy in nuclear recoils would provide strong and arguably compelling evidence for the WIMP nature of DM. At present, however, there is no compelling basis that DM is predominantly WIMPs or that WIMPs must have any of these properties. As yet, there exists no widely accepted evidence of their presence at earth.

In the standard WIMP scenario, the expected nuclear recoil energy spectra fall rapidly with energy. Such recoils, typically not more than a few tens of keV, fall well within the range of abundant and nasty backgrounds due to radioactivity and cosmic radiation. Despite these challenges, experimental limits on interaction cross-section versus WIMP mass have been pushed steadily and impressively lower.

In the event that evidence for nuclear recoils is obtained that cannot be explained with known processes, the question "What quality of evidence is required for acceptance that discovery has been made of the nature of approximately six times more matter than the visible universe?" will become central, but will likely remain without consensus. Then the search for directionality in such nuclear recoils will become of immediate and paramount interest. No known terrestrial background can mimic a directionality signal. It seems prudent to prepare for this eventuality.

To date, almost all approaches pursued for directionality sensitivity attempt to obtain a useful measure of nuclear recoil trajectory *after* drifting an ionization image of the nuclear recoil to a measurement plane with avalanche gain [1]. The degrading effects of diffusion during drift, avalanche gain, and visualization/ reconstruction noise can only be overcome by increasing the range of nuclear recoils through the use of a dilute gas target and the imposition of a maximum allowable drift length to constrain diffusion. These requirements limit the volume to  $\sim 1 \text{ m}^3$  or less, and active mass per detector to  $\sim 100$  grams or less. In contrast, the absence of signals in non-directional direct detection detectors now in operation indicate that hundreds of kg – most popularly liquid xenon (LXe) or liquid argon (LAr) – may be required for adequate sensitivity, and tons are contemplated or near realization for the very near future. Between detectors without directional and those with directional sensitivity, a difference of at least three orders of magnitude in active mass exists; how can this gap be confronted?

A scheme that combines a large, monolithic, active mass with sensitivity to WIMP wind directionality would hence be most welcome. None have been previously conceived, discussed, or proposed, to the best of my knowledge. Here I ask: Can *columnar recombination* be "optimized" to sense nuclear recoil directionality efficiently in a large, massive, monolithic detector? I propose a scheme in which all information is collected in the form of optical signals, based on a high-pressure xenon gas electroluminescent (EL) TPC with a special (and possibly unique) molecular additive.

## 2. Columnar recombination as a tool to sense nuclear recoil direction

Recombination is the capture by an ion of an electron freed by an energetic ionizing particle, an ordinary process in ionized media and generally regarded as either a nuisance or of no special interest. Electron capture is likely when an electron wanders sufficiently near an ion; the relevant proximity for

capture is the Onsager radius, defined as  $r_0 \equiv e^2/\epsilon E$ .  $r_0$  is that distance between a positive ion and a free electron for which the potential energy (negative) is balanced by the electron's kinetic energy  $E$ .  $\epsilon$ , the dielectric constant of the medium, incorporates polarization effects. The Onsager radius is well defined for any sub-excitation energy. To set the scale for a thermalized electron with thermal kinetic energy  $E = kT$  in xenon gas,  $r_0 \approx 70$  nm. In liquid xenon (LXe), polarization decreases  $r_0$  to 54 nm. Jaffe published the first study of columnar recombination (CR) in 1913 [2]. The fundamental insight here is that, under the right conditions, sensitivity exists in recombination processes to the angle between a column of ionization and an electric field – supplied here by a TPC. Perhaps, this effect can be harnessed to substantiate the "flow" of WIMPs, should evidence build that Nature has chosen this model for dark matter.

A large angle between track and field leads electrons transversely away from the ion column. The electrons have relatively few encounters with ions, and a recombination signal is small relative to the ionization signal. Conversely, a small angle implies a higher level of recombination as the electrons drift more or less parallel to the ions, encountering many; a recombination signal is relatively large in comparison to the surviving ionization signal. The measure of directionality is found through a comparison, for each event, of a recombination signal "**R**" to the surviving ionization signal "**I**". The ratio **R/I** for each event carries the message of directionality.

The **R** signal is UV scintillation; the challenge is to maximize the detection efficiency and statistical precision of the **R** signal in a detector of interesting scale. As the detector must be optimized for **R**, it is natural to measure **I** also through optical (UV) signals. **R** is prompt may be considered primary scintillation, but not in the usual sense, and is detected within about 50 ns of the recoil event. The **I** signal is sensed after drift, with delays ranges from about one  $\mu$ s to hundreds.

**R/I** may display a soft dependence on total energy, as well as (by design) a strong dependence on CR. The total energy **E** of the event is a weighted sum: **E** = **aR** + **bI**. The coefficient "a" will depend on the spatial variation of detection efficiency of light within the active volume. This spatial variation may be modest, since optical detection is foreseen to closely approach  $4\pi$ , as elaborated below. Both coefficients will differ substantially depending on whether the event is an electron or nuclear recoil.

### 3. The constraint on density: the columnarity of events

Density enters prominently in the determination of optimum operating conditions. Taking  $r_0$  again as the Onsager radius and defining  $d$  as measure of nuclear recoil track range, the aspect ratio  $A = d/r_0$  provides a useful geometrical measure of "electrostatic columnarity". If the average distance between single ionization events were equal to the Onsager radius, the atomic density could be described as "matched" to the average ionization density. In an average sense, "Onsager spheres" then connect the track segments continuously, *i.e.*, as in a string of beads. In this idealized case of averaged continuous connectivity of the Onsager spheres, the recoil track attains a maximum length.

The optimum for sensing directionality of recoil, however, may not be this idealized case. The atomic density for which directional sensitivity is optimized may correspond to an  $A$  value smaller than the simplest case above. A substantial level of Onsager sphere overlap may be necessary to obtain retention and focusing of the electron cloud by the collective positive charge of the ion column. Presently, this is one of the uncertainties needing exploration.

For example, a 30 keV nuclear recoil in xenon gas for  $\rho = 0.05$  g/cm<sup>3</sup> (about ten bars) has a range of about 2100 nm (see below). The aspect ratio  $A = d/r_0$  is approximately 30 in this case. With  $r_0 = 70$  nm in xenon gas, the minimum  $dE/dx$  for Onsager spheres to "touch" is  $\sim 14$  electron/ion pairs per  $\mu$ m. As discussed in the next section, the maximum ionization density of 30 keV nuclear recoils in xenon gas at 0.05 g/cm<sup>3</sup> (about ten bars) falls in the range of 100 electron-ion pairs/ $\mu$ m, about seven times the geometric *minimum*  $dE/dx$ . In this case of substantial average overlap, an "Onsager tube" of larger radius is the more appropriate image. Ambipolar diffusion is present. The aspect ratio  $A$  is more difficult to estimate, but is still above 5. Clearly the optimum density is unlikely to lie much above  $\rho = 0.05$  g/cm<sup>3</sup>, about 1 ½ % of LXe density.

For comparison, the range in LXe for a 30 keV nuclear recoil track is about 35 nm.  $A = d/r_0 < 1$ , and overlap of Onsager spheres is complete. No electrostatic sense of directionality remains in LXe for nuclear recoils of interest, and directional sensing is beyond hope.

#### 4. What are the conditions for a useful sensitivity?

The necessary conditions appear to be five:

1. WIMPs have masses roughly similar to that of xenon; low mass WIMPs transfer too little energy, and very high mass WIMPs become excessively rare.
2. Nuclear recoils retain, in a statistical sense, significant directionality relative to the incoming WIMP direction.
3. The spatial structure of the primary ions and electrons created after the nuclear recoil event collectively retain a sufficiently linear character;
4. The population of atoms/molecules that experience columnar recombination in a typical event is large enough that useful statistical precision exists;
5. The population of atoms/molecules that experience columnar recombination can be measured with adequate precision and accuracy.

The first condition remains unknown, but is not disfavored theoretically. The code Stopping and Range in Matter (SRIM) provides an approximate answer for condition 2. The author of SRIM does not guarantee accuracy for results obtained for gas densities. Without recourse to a more accurate method, I show results from SRIM in figure 2 for 30 keV xenon atoms, impinging from the left. The recoiling nucleus moves sufficiently slowly,  $\sim \frac{2}{3} \times 10^{-3} c$ , that the atom itself is the recoiling object; the atom becomes ionized as it collides with other xenon atoms. Scattering is substantial, but the ions largely retain their original directions during their initial trajectories – where energy loss is greatest. The average energy lost to ionization is 6.1 keV, reflecting the predominant loss of energy to heat, and a corresponding quenching factor of about 5.

Another shortcoming of SRIM for present purposes is that no information about excitations is available. No experimental data for energy transfer by nuclear recoils to ionization and excitation are available for the gaseous phase of xenon. Liquid and gas phases may display quite different behaviors due to the presence of a conduction band in LXe, absent in the gas phase at  $\rho = 0.05 \text{ g/cm}^3$ . Nevertheless, it is reasonable to assume that the slowly moving atomic recoils produce many more excitations than ionizations. Primary excitations, however, add nothing to directional sensitivity, and represent an important source of recoverable energy that should not be ignored. The stratagem for conversion to additional ionization is elaborated in the next section.

For condition 3, the high density of newly created ions retains the cloud of electrons for a time sufficient for thermalization and subsequent recombination of electrons, under the assumption that the imposed electric field is not too high. For condition four, three variables exist for the optimization of CR: density of xenon, electric field, and fractional addition of a molecular component – easy to accomplish in gas phase xenon. For condition five, the use of a (possibly unique) gaseous molecular additive – trimethylamine – appears to offer the possibility to maximize optical detection efficiency.

#### 5. Trimethylamine – a Penning molecule with ideal fluorescence

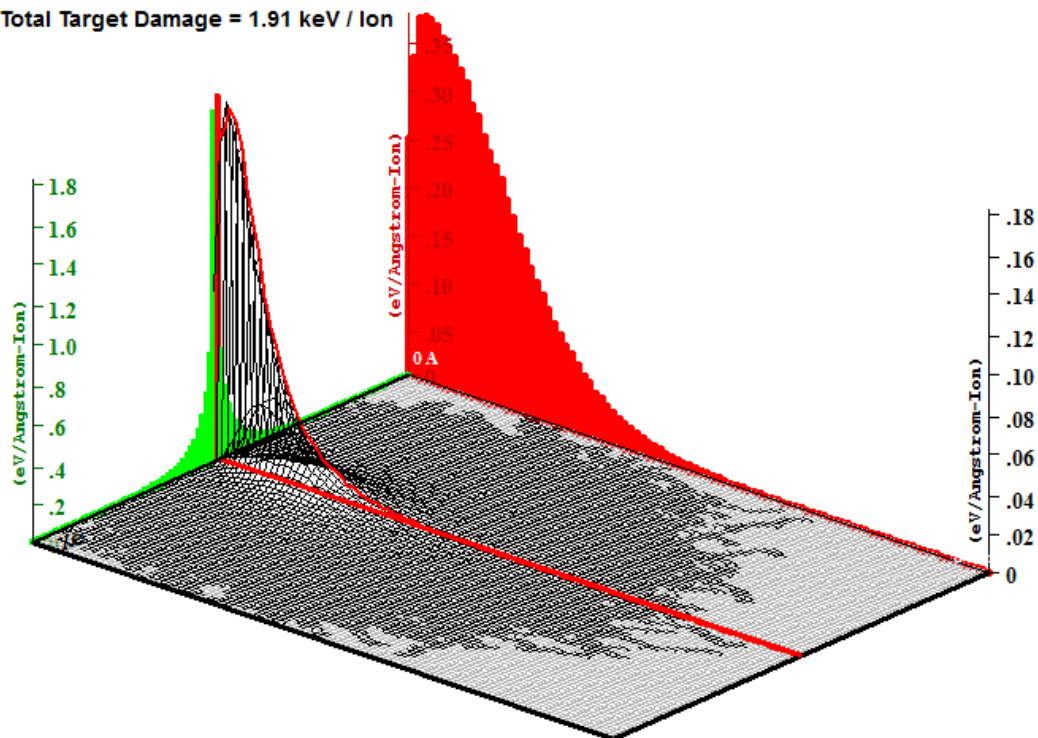
Xenon with trimethylamine (TMA) has been shown to serve as a strong Penning mixture, although the evidence is indirect [3]. A xenon-TMA Penning mixture will convert the energy harbored in the primary excitations to ionization. The newly created ionization can contribute to a CR signal. The presence of TMA also hastens electron thermalization, which in pure xenon is very slow.

## Target Ionization

Total Ionization = 6.1 keV / Ion

Total Phonons = 21.9 keV / Ion

Total Target Damage = 1.91 keV / Ion



Plot Window goes from 0 A to 8 um; cell width = 800 A  
Press PAUSE TRIM to speed plots. Rotate plot with Mouse.

**Ion = Xe (30. keV)**

Figure 2. This SRIM plot shows how energy is distributed in an  $8 \times 8 \mu\text{m}^2$  plane for 100,000 xenon ions of 30 keV entering from the left along the X-axis, the red line. The red histogram displays the deposited ionization along the original ion direction, X, integrated over Y and Z. The green histogram shows the transverse distribution of ionization – note the sharp peak at  $Y = 0$ . The grey histogram indicates ionization density in the plane. The xenon gas density is  $\rho = 0.05 \text{ g/cm}^3$ , about ten bars. An energy weighted range is about  $\sim 2 \mu\text{m}$  for these conditions.

TMA is also one of the three tertiary amines studied for fluorescence [4]. When excited by photons of  $\sim 240 \text{ nm}$ , TMA returns fluorescence with unitary efficiency in a band centered at 300 nm. Providentially, this band matches the peak of the excitation spectrum for common commercial wavelength shifting plastic (WLS). Thus the addition of TMA to the xenon gas permits the TPC interior to be fully covered ( $4\pi$ ) with WLS. Earlier work with triethylamine and argon mixtures showed that electroluminescence is possible without charge gain. This is expected to be the case with TMA + xenon, since the ionization potentials of TMA and TEA are nearly identical, and electrons only reach energies corresponding to excitation levels of TEA/TMA.

This design concept is illustrated in figure 3, showing that only a few dozen PMTs are needed to detect the light captured within the WLS bars. The  $4\pi$  coverage also softens spatial dependence of the

optical detection efficiency. An overall optical detection efficiency of 10% may be achievable, improving the statistical precision of the **R** and **I** signals. The untrapped fraction of WLS light emerging from the end-cap WLS plates provides sufficient intensity for an array of SiPMs to provide the tracking function.

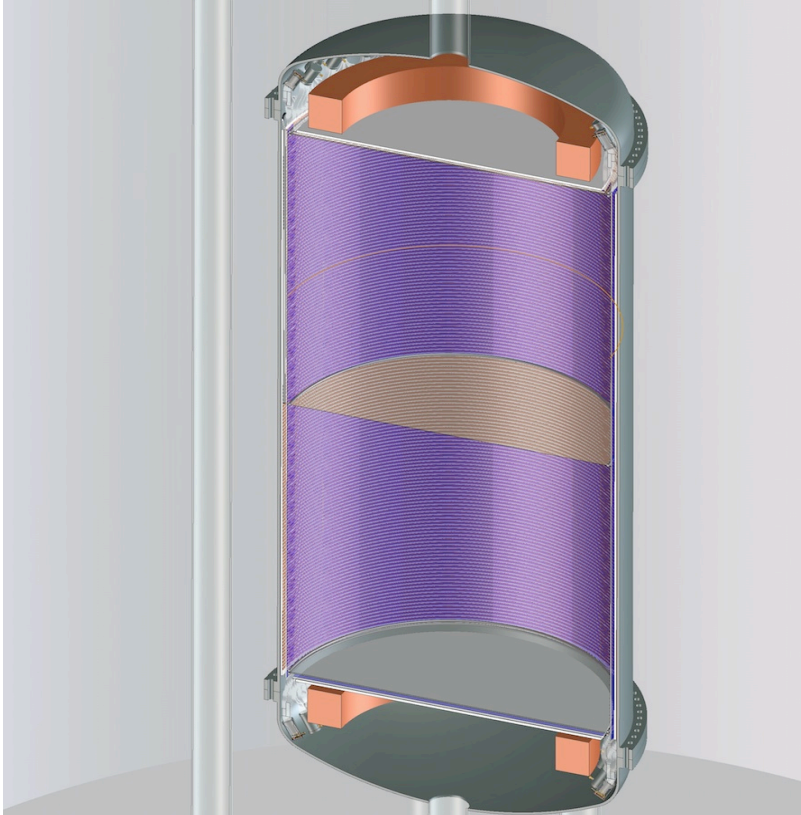


Figure 3. This figure shows a symmetric TPC design for ton-scale active mass at pressure of 10 bars. The width of the TPC is 2.4 m, and each drift distance is 2.5 m. WLS plastic covers the end (anode) regions as well as the walls of the cylindrical field cage to achieve  $4\pi$  coverage. Tracking with small SiPMs is still achievable, using the untrapped light emerging from the WLS end-plates. The PMTs are hidden behind a copper shield, minimizing their contribution to radioactivity budget. Although unknown at present, a head-tail effect may appear as a difference in **R/I** between the upper and lower halves of the TPC.

## 6. Discussion

The detector could work anywhere, from polar to equatorial regions, by orienting to compensate for the angle of the earth's rotation axis. It is necessary to orient the detector such that the drift field is aligned with the expected WIMP flow once per sidereal day. Ideally, the detector should also be anti-aligned once per sidereal day to minimize systematic effects, unfortunately, not possible with a single, fixed, single-ended TPC detector at any latitude. It is possible, however, to construct a symmetric TPC, for which  $\frac{1}{2}$  has the field aligned parallel once a day, and, simultaneously the the other  $\frac{1}{2}$  is anti-parallel. Then the modulation difference between the two halves would automatically display a head-tail effect statistically.

Although  $\alpha$  particles differ from nuclear recoils in important ways, such as their ability to produce numerous  $\delta$ -rays up to about 1 keV – which low-energy nuclear recoils cannot produce, and a range about 100x greater, their use could help to understand the optimum conditions to achieve an optimal directionality sensitivity exploiting CR.

At present, this concept includes several uncertain features, most of which can be addressed experimentally and by simulations. The experimental uncertainties include:

1. Do the nuclear recoils retain a sufficient level of their initial direction, while dissipating most of their kinetic energy?
2. Does TMA deliver a useful level of free ionization by Penning transfer, and what is the optimum fraction that maximizes the Penning transfer to free ionization?
3. What fraction of TMA provides optimum thermalization of the electrons?
4. What is the dependence of optimum electric field as a function of xenon density?

5. What is the dependence of optimum TMA fraction with xenon density?
6. Does the charge exchange process of xenon with TMA occur rapidly enough to convert the ion image to TMA ions?

Despite the number of uncertain features in this concept, it seems prudent and valuable to prepare for the eventuality that direct detection experiments provide evidence supporting the WIMP nature of dark matter. A robust signature of directional anisotropy in WIMP-nuclear recoils seems the essential element for a claim of discovery. I gratefully acknowledge many useful discussions and contributions to this concept by my collaborators in NEXT-100.

### References

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